

Binary interactions as a possible scenario for the formation of multiple stellar populations in globular clusters

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ABSTRACT

Observations revealed the presence of multiple stellar populations in globular clusters (GCs) that exhibit wide abundance variations and multiple sequences in Hertzsprung-Russell (HR) diagram. We present a scenario for the formation of multiple stellar populations in GCs. In this scenario, initial GCs are single-generation clusters, and our model predicts that the abundance anomalous stars observed in GCs are the merged stars and the accretor stars produced by binary interactions, which are rapidly rotating stars at the moment of their formation and are more massive than normal single stars in the same evolutionary stage. We find that due to their own evolution, these rapidly rotating stars have different surface abundances, effective temperatures and luminosities from normal single stars in the same evolutionary stage. The stellar population with binaries can reproduce two important observational evidences of multiple stellar populations, the Na-O anticorrelation and the multiple sequences in HR diagram. This suggests that binary interactions may be a possible scenario for the formation of multiple stellar populations in GCs.

Subject headings: globular clusters: general – binary: general – stars: evolution – stars: rotation

1. Introduction

Observational evidences for multiple stellar populations in globular clusters (GCs) challenge the traditional view of GCs hosting simple stellar populations, which are formed in one generation from a cloud of uniform composition (single-generation cluster). One important evidence is the presence of star-to-star abundance variations. The most famous example is

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the Na-O anticorrelation that oxygen-depleted stars have higher sodium abundances, which is exhibited among the main sequence (MS) turnoff (TO) stars, sub-giant branch (SGB) stars and red-giant branch (RGB) stars in some GCs (Carretta et al. 2004; Gratton et al. 2004). Another important evidence is that some GCs show multiple MSs (Piotto et al. 2007), multiple SGBs (Milone et al. 2008; Marino et al. 2009), or anomalously wide RGB (Yong et al. 2008; Lee et al. 2009) in the Hertzsprung-Russell (HR) diagram.

Several scenarios have been proposed to explain the formation of multiple stellar populations (Gratton et al. 2012), and they can be classified into two contrasting hypotheses: *Primordial* Scenario vs. *Evolutionary* Scenario (Kraft 1994; Carretta et al. 2004). In the *Primordial* Scenario, multiple stellar populations in GCs are formed in the different materials that are primordial chemical inhomogeneities, for example, a merger of two separate GCs (Lee et al. 1999; Mackey & Broby Nielsen 2007) or the self-pollution of the intra-cluster gas occurring in the early evolution of clusters (D’Antona et al. 2002; Decressin et al. 2007; de Mink et al. 2009). However, a merger event would not be expected to occur in the halo of the Milky Way due to the very large relative velocities of GCs (Gratton et al. 2012). For the self-enrichment of GCs, it is difficult to explain the high fraction of the second-generation formed from the gas polluted by the first-generation stars (Bastian & de Mink 2009), and the nature of possible polluters remains unclear (Sills & Glebbeek 2010; Gratton et al. 2012).

In the *Evolutionary* Scenario, initial GCs are believed to be single-generation clusters, and multiple stellar populations in GCs are attributed to the evolution of stars affected by some physical processes, such as the first dredge-up, Sweigart-Mengel Mixing (Sweigart & Mengel 1979), primordial rotation (Bastian & de Mink 2009). However, it is necessary to explain why only some of stars in GCs are affected by these physical processes. Moreover, Decressin et al. (2007) suggested that the MS TO stars in GCs are not hot enough for producing the observed Na-O anti-correlation, because the central temperature (about 25×10^6 K) of a $0.85 M_{\odot}$ TO stars is higher than the required temperature of CNO cycle (about 20×10^6 K), but is lower than that of the production of ^{23}Na from proton-capture on ^{20}Ne (about 35×10^6 K).

Binary interactions have been used to explain the formation of multiple stellar populations as a kind of *Primordial* Scenario. Chemically enriched material ejected from massive binaries have been proposed to form a second population of stars (de Mink et al. 2009), or to be accreted by low-mass pre-main-sequence stars (Bastian et al. 2013). However, binary interactions are not considered as a kind of *Evolutionary* Scenario. They are not investigated to produce the abundance anomalous stars *directly*, although they have been proposed as an explanation for extended MS in the HR diagrams of intermediate age clusters (Yang et al. 2011; Li et al. 2012).

Binary systems can produce stars more massive than normal single stars in the same evolutionary stage by binary interactions, e.g. the merged stars or the accretor stars. These stars are not hot enough for the production of ^{23}Na from proton-capture on ^{20}Ne , but they are hot enough for proton-captures on ^{16}O and ^{22}Ne , which respectively lead to the destruction of ^{16}O and to the production of ^{23}Na at temperatures $>20 \times 10^6 \text{ K}$ (Prantzos & Charbonnel 2006). Furthermore, these stars produced by binary interactions will be rapid rotating because binary interactions can convert orbital angular momentum into their spin angular momentum (de Mink et al. 2013). Rotationally induced mixing can bring part of the nuclear-processed products from the core to the surface (Decressin et al. 2007), and stellar rotation was used to explain the observed nitrogen enrichment found in several massive MS stars (Brott et al. 2009). Therefore, these rapidly rotating stars reproduce the properties of the abundance anomalous stars observed in GCs (e.g. the Na-O anticorrelation), and binary interactions will be a possible scenario for the formation of multiple stellar populations in GCs as a kind of *Evolutionary Scenario*.

In this paper, we adopt a simple model for this scenario to investigate the formation of multiple stellar populations. In Section 2, we explore the formation of rapidly rotating stars from binary interactions by performing binary evolution calculations, and calculated the subsequent evolution of these rapidly rotating stars to obtain their parameters (e.g. effective temperatures, luminosities and surface abundances). Then, we estimate the distributions of the binary population by performing the binary population synthesis study. In Section 3, we give discussion and conclusions.

2. THE MODEL AND SIMULATION

In our scenario, the anomalous stars observed in GCs are the merged stars and the accretor stars produced by binary interactions, and these binary products are rapidly rotating and more massive than the normal stars. These binary products have different effective temperatures, luminosities and surface abundances from single stars in the same evolutionary stage due to their own evolution. Thus, the stellar population with binaries (the binary population) can reproduce the observations of multiple stellar populations, because the binary population includes two populations: (1) normal single stars with normal abundance (initial abundance of GCs); (2) the merged stars and the accretor stars (produced by binary interactions) that have abnormal surface abundances by their own evolution.

2.1. Binary evolution calculations

We considered three evolutionary channels for the formation of rapidly rotating stars from binary interactions: (1) a binary evolves into contact and then merges into a rapidly rotating star (contact merger channel for the merged stars) (Jiang et al. 2012; de Mink et al. 2013); (2) a binary evolves into Roche lobe overflow (RLOF) and experiences unstable mass transfer while both components are still MS stars, and then merges into a rapidly rotating star (unstable RLOF merger channel for the merged stars) (Jiang et al. 2012); (3) a binary evolves into RLOF and experiences stable mass transfer, and the secondary obtains the mass and angular momentum transferred from the primary, and then becomes a rapidly rotating star (stable RLOF channel for the accretor stars) (de Mink et al. 2013).

In these channels, a binary needs to evolve into contact phase or unstable RLOF phase while both components are still MS stars, or evolve into stable RLOF phase while the secondary is still a MS star (Jiang et al. 2012; de Mink et al. 2013). This is because for MS stars, the binding energy of the envelope might be large enough to form rapidly rotating stars. To determine whether the binary evolves into these phase, it is necessary to perform detailed binary evolution calculations. We use Eggleton’s stellar evolution code (Eggleton 1971, 1972; Eggleton et al. 1973) that has been updated with the latest input physics during the last four decades (Han et al. 1994; Pols et al. 1995, 1998; Nelson & Eggleton 2001; Eggleton & Kiseleva-Eggleton 2002). In our calculations, we used the metallicity $Z = 0.001$ (corresponding to typical GCs) and considered the nonconservative effects, includes a model of dynamo-driven mass loss, magnetic braking and tidal friction for the evolution of stars with cool convective envelopes (Eggleton & Kiseleva-Eggleton 2002).

Altogether, we have calculated the evolution of 5200 binary systems, thus obtained a large, dense model grid that covers the following ranges of initial primary mass (M_{10}), initial mass ratio ($q_0 = M_{20}/M_{10}$) and initial orbital period (P_0): $\log M_{10} = -0.3, -0.25, \dots, 0.2$; $\log q_0 = \log (M_{20}/M_{10}) = 0.05, 0.10, \dots, 0.5$; and $\log (P_0/P_{\text{ZAMS}}) = 0.05, 0.10, \dots$, where P_{ZAMS} is the orbital period at which the initially more massive component would just fill its Roche lobe on the zero-age MS. These ranges of initial parameters cover the systems that can form rapidly rotating stars in old stellar population by Case A binary evolution. According to these binary models, the parameters of rapidly rotating stars are established when the binary evolves into contact, unstable RLOF, or the end of stable RLOF. For simplicity, in the contact merger channel and the unstable RLOF merger channel, we assume that there are 10% mass loss during the merger phase (Jiang et al. 2012; de Mink et al. 2013) and the binary products rotate at 80% of break-up velocity. For the stable RLOF channel, we calculate the angular momentum obtained by the secondary, and then calculate its rotational velocity. We only consider the secondaries that can get enough angular momentum to rotate

at 80% of break-up velocity.

2.2. Rotation evolution calculations

To calculate the subsequent evolution of rapidly rotating stars produced by binary interactions, we have used the Modules for Stellar Experiments in Astrophysics code (MESA version 4631) (Paxton et al. 2011). This code implements the effects of rotation in the transport of angular momentum and chemical mixing, and it has been used to study the effects of rotational mixing (Chatzopoulos et al. 2012; Chatzopoulos & Wheeler 2012). We do not consider the effect of the helium-rich core of the original components on the subsequent evolution of rapidly rotating stars, and we assume that these rapidly rotating stars have abundances similar to zero age MS stars. In addition, we consider that the effect of rotation on low-mass stars with convective envelopes might be weaker due to magnetic braking (Hurley et al. 2000; Bastian & de Mink 2009). We calculate the stellar evolutionary models with $M = 0.6, 0.7 \dots 1.6 M_{\odot}$ for $Z = 0.001$ that cover rapidly rotating stars produced by binary interactions in old stellar populations. For simplicity, these models run for two different degrees of rotation: non-rotating and 80% of break-up velocity, which are used to investigate the evolution of surface abundances of single stars and rapidly rotating stars produced by binary interactions. All evolutionary tracks have been computed up to the point of core helium ignition.

To illustrate the evolutionary tracks of these stars, we show four evolution examples of surface mass fractions (sodium versus oxygen abundances) in Fig. 1. During the evolution of rapidly rotating star with $M = 1.3 M_{\odot}$ (dotted line), the surface mass fraction of sodium ($X_{\text{Na}23}$) increases from 1.22×10^{-6} to 5.95×10^{-6} , and that of oxygen ($X_{\text{O}16}$) decreases from 4.67×10^{-4} to 9.54×10^{-5} . This is because the destruction of O and the production of ^{23}Na in the central region result from proton-captures on ^{16}O and ^{22}Ne (Langer et al. 1993; Prantzos & Charbonnel 2006; Decressin et al. 2007), and they are brought to the surface by rotational mixing. In other examples, rapidly rotating stars with $M = 1.0, 1.1, 1.2 M_{\odot}$ evolve in a similar way as in the previous example, although the variation ranges of surface abundances decrease with decreasing mass. Hence, these rapidly rotating stars can be oxygen depletion and sodium enhancement. For single stars with no rotation (open circles in Fig. 1), the surface mass fractions of sodium and oxygen do not show significant variations.

2.3. Binary population synthesis

In the binary population synthesis study, we have performed a Monte Carlo simulation. We adopt the following input for the simulation (see Han et al. 1995). (1) The initial mass function (IMF) of Miller & Scalo (1979) is adopted. (2) The mass-ratio distribution is taken to be constant. (3) We take the distribution of separations to be constant in $\log a$ for wide binaries, where a is the orbital separation. Our adopted distribution implies that ~ 50 per cent of stellar systems are binary systems with orbital periods less than 100 yr. We follow the evolution of a million sample binaries according to grids of binary models and the evolution models of rapidly rotating stars described above.

The simulation gives the distributions of many properties of the binary population, e.g. the masses, the effective temperatures, the luminosities, the surface abundances, etc. Fig. 2 are selected distributions of the binary population at 10 Gyr that may be helpful for understanding the scenario of binary interactions for the formation of multiple stellar populations. Fig. 2(a) shows the distribution of single stars and binary products in the Na-O plane. Single stars (open circles) are concentrated at the bottom right corner and do not show significant variations. However, binary products have large star-to-star variations. The distribution of binary products first extends upward to high sodium abundance region from the original abundance location, and then turns left to the oxygen depletion region. Thus, the binary population with binary interactions can show a Na-O anticorrelation.

To investigate the distributions of binary products with different abundances in HR diagram, we classify them into four groups based on the surface mass fraction of Na and O, which are denoted as pluses with different colours. The distribution of the binary population with binary interactions in HR diagram is shown in Fig. 2(b). It is obvious that this population has at least two MSs, three TOs, three SGBs and extended RGB, which are produced by single stars (open circles) and binary products (pluses). More importantly, these sequences have a large spread in sodium and oxygen abundances. This is consistent with the fact that the Na-O anticorrelation is observed among MS TO stars, SGB stars and RGB stars in some GCs (Carretta et al. 2004; Gratton et al. 2004). Observed red giants in 17 GCs given by Carretta et al. (2009) are shown in Fig. 2(c), and they have a distribution similar to that of our simulated binary populations. If we assume that the binary populations (black line and blue lines) with different initial abundances, such as in different GCs, have the same variation ranges of surface abundances, then we would find that these binary populations in the simulation are in good agreement with the observed stars in 17 GCs as shown in Fig. 2(c).

We noted that single stars and binary products in the binary population have different mass distributions as shown in Fig. 2(d), and binary products are more massive than single

stars. For the binary population with $\log L/L_\odot > 0$, the mass range of single stars is from 0.75 to $0.9 M_\odot$, while the mass range of binary products is from $0.8 M_\odot$ to $1.35 M_\odot$, although these single stars and binary products have the same range of evolutionary stages. The maximum mass of binary products is larger than that of single stars by $\sim 0.45 M_\odot$. We do not compare stars with $\log L/L_\odot < 0$ because the sample of very low-mass binary products is not complete in our calculations. Although the effect of rotation on low-mass stars might be weaker due to magnetic braking (Hurley et al. 2000; Bastian & de Mink 2009), massive binary products could have significantly different surface abundances from single stars. Binary products are more massive than single stars in the same evolutionary stage, and they rotate rapidly, i.e. close to break-up velocity. The destruction of ^{16}O and the production of ^{23}Na in the central region result from proton-captures on ^{16}O and ^{22}Ne , and the products of nuclear burning are brought to the surface by rotational mixing. This can explain why the abundance variations take place in these stars, and not in single stars at the same evolutionary stage.

3. Discussion and conclusions

In this paper, we presented binary interactions as a possible scenario for the formation of multiple stellar populations in GCs. In this scenario, binary interactions can convert orbital angular momentum into spin angular momentum and produce rapidly rotating stars. These stars might have different properties from single stars, such as surface abundances, temperatures and luminosities, because they experienced binary interactions and their evolution is affected by rotationally induced mixing. The existence of binary products and single stars results in multiple stellar populations in GCs, although initial GCs are single-generation clusters. In our simple model, we carried out binary evolutionary calculations and constructed the evolutionary models of rapidly rotating stars formed by binary interactions. By performing a Monte Carlo simulation, we obtained the distributions of the binary population and investigated the formation of multiple stellar populations from binary interactions.

Stellar rotation have been shown that can explain the broad MS and spread TO observed in intermediate age stellar clusters (Bastian & de Mink 2009; Li et al. 2012). However, Bastian & de Mink (2009) suggested that this is unlikely to cause multiple stellar populations observed in old GCs, because the stars in GCs are low mass and are not expected to be rapidly rotating stars. We show that old binary population could show multiple sequences in HR diagram as shown in Fig. 2(b), because binary interactions could produce rapidly rotating stars. Binary interactions, including mass transfer (Pols et al. 1991; de Mink et al. 2013) or merger (Tylenda et al. 2011; Jiang et al. 2013), have been used to investigate the formation of rapidly rotating stars. Moreover, observed evidences have shown that binary

interactions are very common in GCs. Many contact binaries have been observed in GCs (Rucinski 2000), and these binaries are believed to merge into a rapidly rotating star (contact merger channel). Mathieu & Geller (2009) show that many of blue stragglers are rotating faster than normal MS stars, which might be formed by mass transfer (Geller & Mathieu 2011). Therefore, binary interactions could explain multiple sequences in HR diagram, which is important evidence of multiple stellar populations.

Other important evidence of multiple stellar populations in GCs is the presence of star-to-star abundance variations, and the most famous example is the Na-O anticorrelation. We show that old binary population can reproduce a Na-O anticorrelation as a result of the formation of rapidly rotating stars from binary interactions. If the binary populations with different initial abundances, such as in different GCs, are assumed to have the same variation ranges of surface abundances, we found that these binary populations in the simulation are in good agreement with the observed stars in 17 GCs given by Carretta et al. (2009). In our scenario, this anticorrelation could be found in TO stars, SGB stars and RGB stars, which is in agreement with the observation that show the Na-O anticorrelation in these evolutionary stages (Carretta et al. 2004; Gratton et al. 2004). Moreover, our model predicts that these abundance anomalous stars should be more massive than MS TO stars, and they should be blue stragglers or blue straggler progeny. Therefore, binary interactions could explain the existence of the Na-O anticorrelation in GCs. This suggests that binary interactions may be a possible scenario for the formation of multiple stellar populations, and the traditional view of single-generation cluster could explain the photometric and spectroscopic observations of multiple stellar populations by considering the effects of binary interactions.

Observed multiple stellar populations show the cluster-to-cluster variations (e.g. Carretta et al. 2009), and these variations also need to be explained (Sills & Glebbeek 2010). This cluster-to-cluster variations might be due to the dependence of binary interactions on the cluster properties, such as age, initial abundance, initial fraction of binaries and initial orbital separation distribution. These parameters determine the nature of binary interactions and the subsequent evolution of binary products. When the initial fraction of binaries is very low, the binary population would have few binary products and be similar to a simple, single stellar population. The investigation of the properties of binaries in 13 low-density GCs revealed that the fraction of binaries ranges from 0.1 to 0.5 in the core depending on the cluster (Sollima et al. 2007). Moreover, the stellar density in GCs is sufficiently high to affect the binaries that can be destroyed, created or modified by dynamical interaction (e.g. Hut et al. 1992). Higher stellar densities could result in more efficient binary dissolution and thus a lower binary fraction (Marks & Kroupa 2011). Consequently, the binary population might have different distributions and different fractions of binary products in various clusters. A more detailed study of the binary population with binary interactions might help

to understand the dependence of binary interactions on the cluster properties in the further studies.

It is clear that our model is still quite simple and does not investigate in much detail so far. In our investigation, we do not consider the effect of the helium-rich core of the original components on the subsequent evolution of binary products. Our simulation shows that 36 per cent of all rapidly rotating stars are formed by binary merger (including contact merger channel and unstable RLOF merger channel). These rapidly rotating stars formed by binary merger might contain the helium-rich core of the original primary, and their remaining relative lifetimes are smaller than those of single stars with the same masses (e.g. Sills et al. 1997; Glebbeek & Pols 2008; de Mink et al. 2013). For rapidly rotating stars produced through stable RLOF, this effect need not to be considered because they are the less-massive components of binaries and their cores are still hydrogen rich at the onset of mass transfer (e.g. Sills et al. 1997; Glebbeek & Pols 2008; de Mink et al. 2013). For rotating velocity, we simply assume that all binary products rotate initially at 80% of break-up velocity. A lower initial rotating velocity or a faster spin-down will lead to a weaker variation of surface abundances. These effects need more detailed investigation in further study. In addition, the observations suggested that the fraction of binaries in GCs may be lower than that in the field and open clusters (Rubenstein & Bailyn 1997). This might be because GCs are much older than the field and open clusters, and consequently more binaries in GCs are not expected to be recognized as binaries due to their large luminosity ratio and their large orbital periods, or they may not even be binaries due to merger (de Mink et al. 2013).

We thank an anonymous referee for his/her valuable comments. This work was supported by the Natural Science Foundation of China (Nos 11073049, 11033008, 11103073, 11390374 and 11373063), Science and Technology Innovation Talent Programme of the Yunnan Province (No. 2013HA005) and the Western Light Youth Project.

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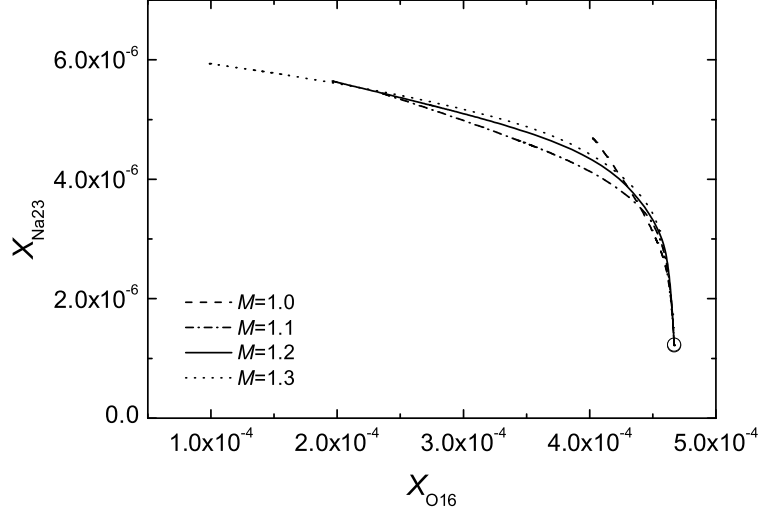


Fig. 1.— Evolutionary examples of rapidly rotating stars from their formation in the surface mass fraction ($X_{\text{Na}23} - X_{\text{O}16}$) plane. The dashed, dash-dotted, solid and dotted lines represent the evolution of rapidly rotating stars with 1.0, 1.1, 1.2 and 1.3 M_{\odot} , respectively. The evolutionary tracks of rapidly rotating stars begin from the bottom right corner to top left corner. During the evolution of these stars, they show an increase of sodium abundance by ~ 0.67 dex and a decrease of oxygen abundance by ~ 0.74 dex. Therefore, they can reach significant oxygen depletion and sodium enhancement, although their variation ranges of surface abundances are different and depend on their masses. Open circles present the evolution of single stars that do not show significant variations.

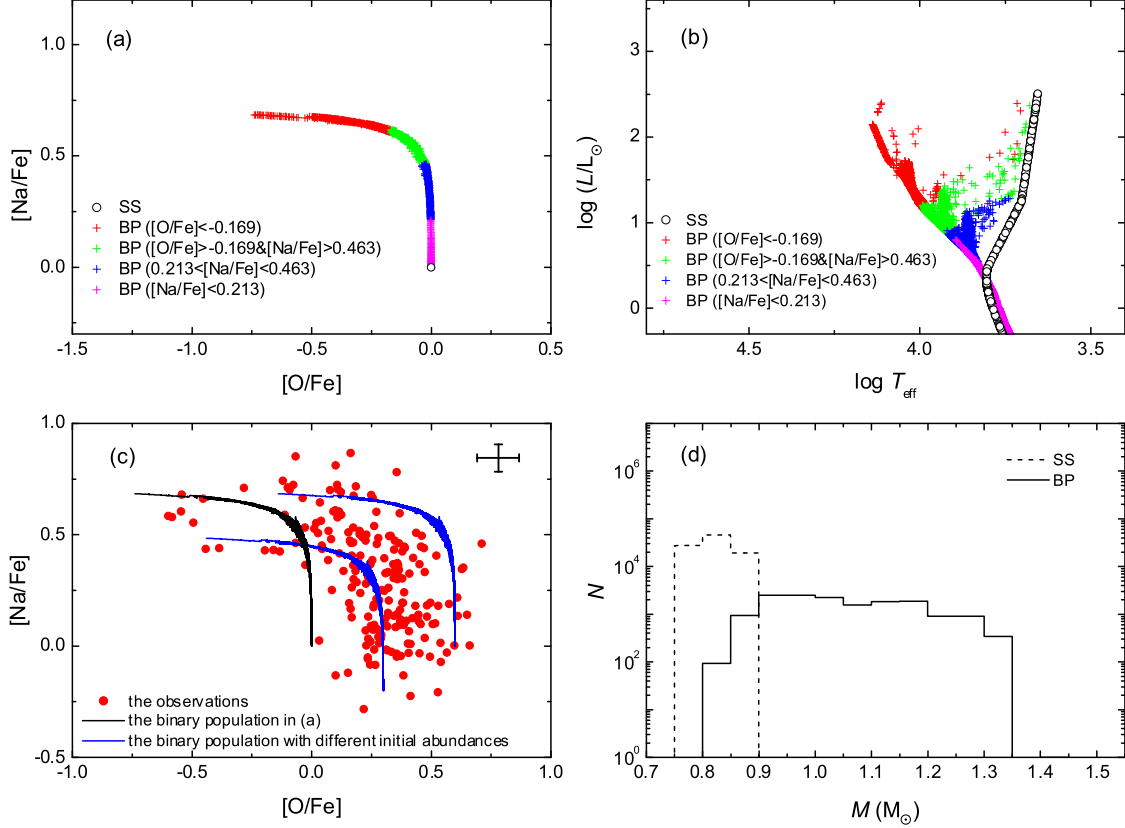


Fig. 2.— Distribution of single stars (SS) and binary products (BP) in the simulation of the binary population with binary interactions at 10 Gyr. (a) the simulated distribution in the surface abundances (Na-O) plane; (b) the simulated HR diagram; (c) the observational abundances for 202 red giants in 17 GCs (Carretta et al. 2009); (d) the simulated distribution of mass. For panels (a) and (b), open circles correspond to single stars, and pluses to binary products that are classified into four group (red, green, blue, and magenta) according to their surface mass fractions of Na and O. In panel (c), red points show the observed red giants in 17 GCs given by Carretta et al. (2009), and typical errors are indicated in this panel. Black line presents the binary population in panel (a), for comparison. Blue lines show two binary populations with different initial abundances that are assumed to have the same variation ranges of surface abundances of the binary population in panel (a). In panel (d), the solid histograms and the dashed histograms are the distributions of the masses for binary products and single stars with $\log L/L_{\odot} > 0$.